PCAS 20 (2017/20x18)

Supervised Project Report
(ANTA604)

GNSS Machine Guidance in the Antarctic

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Executive Summary

Well, I just got to this last part and have run out of time to complete the executive summary before submitting the project. Would also like to have completed the references section throughly.

However, The project was successfully completed and achieved the goals I set out to achieved.

I am working with John Evans to prepare a Trimble GFX machine control system for him to trial at Scott Base in spring 2018.

Introduction

Opportunities exist for machine control systems that can provide safe navigation during extreme weather, and also provide guidance over dangerous terrain. Global Navigation Satellite System (GNSS)-based machine control systems can record a route and then "play" it back as many times as required. A simple application would be to record the route between Scott Base and McMurdo base. During extreme weather with zero visibility a Hagglund equiped with a GNSS machine-guidance system could simply play back the recorded route and safely complete the journey. Another application would be an autonomous vehicle making its way across the ice checking for crevasses with ground penetrating radar. The autonomous vehicle would send a safe route back for a following vehicle to follow.

GNSS position data is used by many people during their daily field operations already in the Antarctic. For most applications the absolute accuracy and repeatability of the data is not critical. In fact, few users question the integrity of the data because 5 to 10 metre accuracy meets their requirements and is good enough. Accuracy and repeatability become more important when the position data is being used for machine-guidance and control. To be useful, machine control requires consistent accuracy of less than +/- 500mm, and +/- 25mm would be ideal. Achieving this level of accuracy in the high latitudes of the Antarctic presents challenges. This project will discuss and evaluate the factors affecting the GNSS accuracy and integrity.

Global Navigation Satellite System (GNSS)

The GNSS system has had a major impact on military and civilian navigation, positioning, and timing infrastructure since it become fully operational with the American GPS system in 1983. The reliability and accuracy of the GPS has improved with the addition of the Russian Glonass system. Further improvements are expected with the completion of the European Galileo system and the Chinese BeiDou systems in 2020. The Japanese QZSS and Indian IRNS system will aded further improvements when they are completed. Collectively these 6 constellations of satellite systems have become known as the Global Navigation Satellite System (GNSS).

As accuracy and reliability have continually improved, the price of receivers has decreased, and this has opened up more markets and more applications. The price of a dual frequency, multi-constellation GNSS receiver has decreased to the point where it is now included in most cell phones. Accuracy has improved allowing the same cell phone GNSS receiver (with the right attachment) to position itself to within +/- 38mm.

How GNSS works (Fig. 1)

A constellation of 24 satellites (GPS) orbits the earth twice a day at an altitude of approximately 12,000km. The satellites broadcast radio signals providing their location and the precise time. A GNSS receiver on earth receives the radio signal, noting the exact time of arrival, and uses this information to calculate the distance from the satellite. Once the GNSS receiver knows its distance from at least four satellites, it can use geometry to determine its own location on earth. The accuracy of the position is affected by atmospheric variations and errors in the system. The errors can be reduced by using more satellites, satellites in better positions, high-accuracy receivers, and by using an augmentation signal to compensate for the errors.

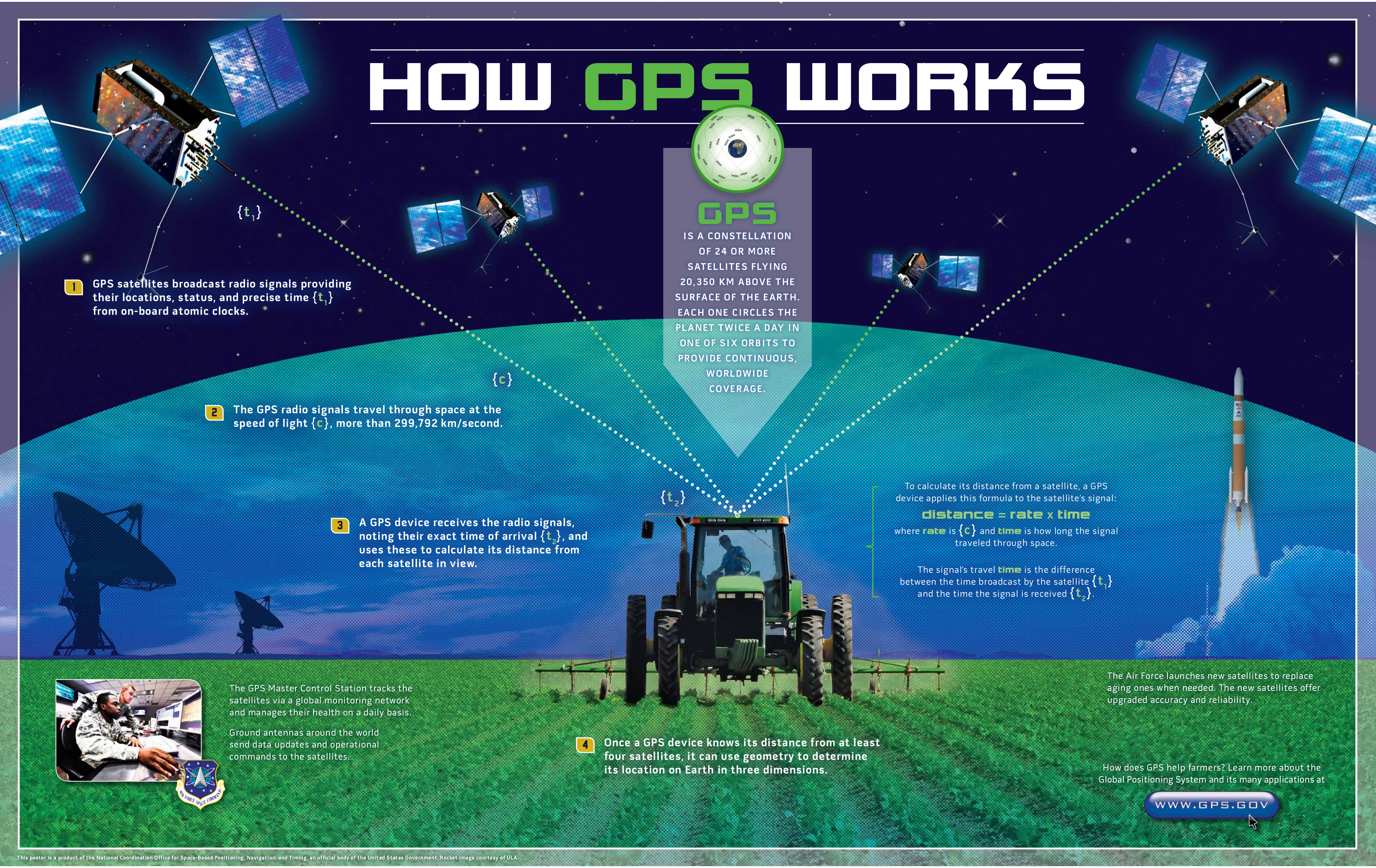
There are some limitations and constraints in the GNSS which the user can change to improve the operation of the GNSS.
The GNSS satellites must be in a direct line of sight without obstructions to the GNSS antenna for the GNSS receiver to accurately calculate the distance between them. The signals do not pass through metal or conductive material like carbon fibre, so it is essential to mount the GNSS antenna where it has a clear view of the sky. The signals can pass through snow and foliage, but this can introduce multipath errors - described below.

A minimum of 4 satellites is required to calculation a position. Buildings and topography can block the line of sight from the GNSS antenna to the satellites. With the additional GNSS constellations (Fig. 2) this is not a problem anymore.

The satellite radio signals can bounce off reflective metal surfaces on their way to the GNSS antenna creating additional length in the distance between satellite and receiver. This creates multiple paths (multipath) for the signal to reach the antenna and introduces error in the position calculation. High accuracy GNSS antennas have ground planes and multipath rejection technology to improve accuracy.

There are other limitations and constraints the user cannot change about the operation of the GNSS, and these just have to be endured. Solar storms, scintilation (Coordinates), unintentional and intentional interference, ionospheric disturbances, and possible restriction of service during military operations.

Figure 1. How GPS works. (Source - GPS.Gov) Follows on the next page.



HOW GPS WORKS
GPS
IS A CONSTELLATION OF 24 OR MORE SATELLITES FLYING 20,350 KM ABOVE THE SURFACE OF THE EARTH. EACH ONE CIRCLES THE PLANET TWICE A DAY IN ONE OF SIX ORBITS TO PROVIDE CONTINUOUS, WORLDWIDE COVERAGE.
{t1}
1 GPS satellites broadcast radio signals providing their locations, status, and precise time {t1} from on-board atomic clocks.
{c}
2 The GPS radio signals travel through space at the speed of light {c}, more than 299,792 km/second.
{t2}
3 A GPS device receives the radio signals, noting their exact time of arrival {t2}, and uses these to calculate its distance from each satellite in view.
To calculate its distance from a satellite, a GPS device applies this formula to the satellite's signal:
distance = rate x time
where rate is {c} and time is how long the signal traveled through space.
The signal's travel time is the difference between the time broadcast by the satellite {t1} and the time the signal is received {t2}.
4 Once a GPS device knows its distance from at least four satellites, it can use geometry to determine its location on Earth in three dimensions.
The GPS Master Control Station tracks the satellites via a global monitoring network and manages their health on a daily basis.
Ground antennas around the world send data updates and operational commands to the satellites.
The Air Force launches new satellites to replace aging ones when needed. The new satellites offer upgraded accuracy and reliability.
How does GPS help farmers? Learn more about the Global Positioning System and its many applications at
WWW.GPS.GOV
This poster is a product of the National Coordination Office for Space-Based Positioning, Navigation, and Timing, an official body of the United States Government. Rocket image courtesy of ULA.

Figure 2. GNSS Sky Plot from a Trimble GFX GNSS receiver showing satellite constellaions. (Source - Trimble GFX screen snap)

Dilution of Precision - The DOPs (Fig. 3)
As the satellites orbit the earth there are times when they are closer together in the sky. The poor geometry of the satellites reduces the precision of the position. At other times a good distribution of satellites creates better geometry, and the error in precision is reduced. The effect of geometry of the satellites on precision error is called geometric dilution of precision. The addition of the GNSS, Galileo, and BeiDou satellite constellations has increased the number of satellites in view and improved the precision of the GNSS.

DOPs can be expressed for a number of measurements:

- HDOP - horizontal dilution of precision
- VDOP - vertical dilution of precision
- PDOP - position (3D) dilution of precision
- TDOP - time dilution of precision

DOP Value	Rating	Description
< 1	Ideal	Highest possible confidence level to be used for applications demanding the highest possible precision at all times.
1-2	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.
2-5	Good	Represents a level that marks the minimum appropriate for making business decisions. Positional measurements could be used to make reliable in-route navigation suggestions to the user.
5-10	Moderate	Positional measurements could be used for calculations, but the fix quality could still be improved. A more open view of the sky is recommended.
10-20	Fair	Represents a low confidence level. Positional measurements should be discarded or used only to indicate a very rough estimate of the current location.
>20	Poor	At this level, measurements are inaccurate by as much as 300 meters with a 6-meter accurate device (50 DOP × 6 meters) and should be discarded.

Figure 3. DOP Descriptions.

Accuracy
When first operational in 1985, a military receiver was capable of +/- 5m accuracy with a 66% confidence level. Simple physical limitations in the GPS system introduced errors in the position accuracy of the GNSS receiver. The time for the signal to reach earth is known, and the speed is constant; so, obtaining the distance is a simple calculation. However, the time calculation is influenced by many factors including disturbances in the atmosphere, obstructions (multipath) around the receiver antenna, clock accuracy, processing speed, and processing errors in the GPS receiver.

Design factors affecting GPS receiver accuracy:

- single constellation versus multi constellation
- single channel versus multi channel
- processor speed
- GPS antenna design
- multipath rejection
- software algorithms.

A modern dual-frequency, multi constellation GNSS receiver can calculate its position on earth with an estimated error of less than +/- 25mm with a 95% confidence level.

Augmentation
"A GNSS augmentation is any system that aids GNSS by providing accuracy, integrity, availability, or any other improvement to positioning, navigation, and timing that is not inherently part of GNSS itself". (Augmentation). Prior to 2006, the United States military degraded the civilian GPS signal using a process called Selective Availability (SA) which reduced the accuracy to +/- 300m. This was done to prevent the US's enemy using the accuracy of the GPS system against the US or its allies. As the demand for higher accuracy increased, civilian companies founds ways to circumvent SA. The civilian receivers when combined with a augmentation signal became more accurate than the military receivers, and the civilian uses for GPS became so widespread that the US government decided to stop using SA, and it was turned off in May 2000.

An augmentation signal is generated from a land-based GNSS receiver - A GNSS Reference station - at a known fixed point. From knowing its true position on earth and comparing this with the GNSS generated position, the reference station can calculated the error in the GNSS position. The error, or correction signal is then transmitted to the rover GNSS receiver in the field via a telemetry link. The rover then applies the correction to its GNSS position thus improving its positional accuracy. The GNSS satellites are orbiting the earth at approximately 30,000km/hr, 12,000km away, and transmitting their position at 5Hz, so there is a lot of arithmetic required to generate the correction signal and then get it to the rover to process its corrected position. The newest augmentation services are able to provide improvements in accuracy down to +/- 500mm in most populated areas of the world, and less than +/- 25mm in localised areas.

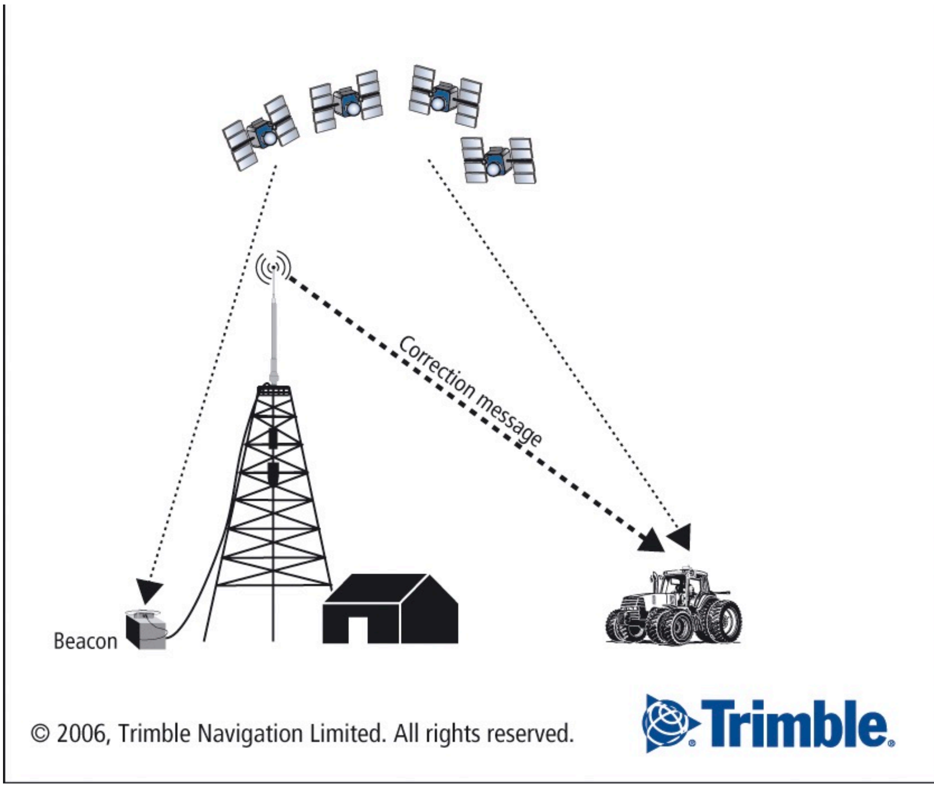


Figure 4. Ground-Based Augmentation (GBAS) (source - Trimble Navigation)

Terrain Compensation
Terrain compensation calculates the difference the GNSS antenna's position and the position of the vehicle due to the effects of roll, pitch, and yaw. As a vehicle moves along its intended path it will encounter terrain that makes the vehicle move in the three axes of roll, pitch, and yaw. For accurate self-steering the control system needs to calculate the effects of roll, pitch, and yaw on the position reported by the GNSS antenna. The corrected position is then used to position the vehicle on the correct path.

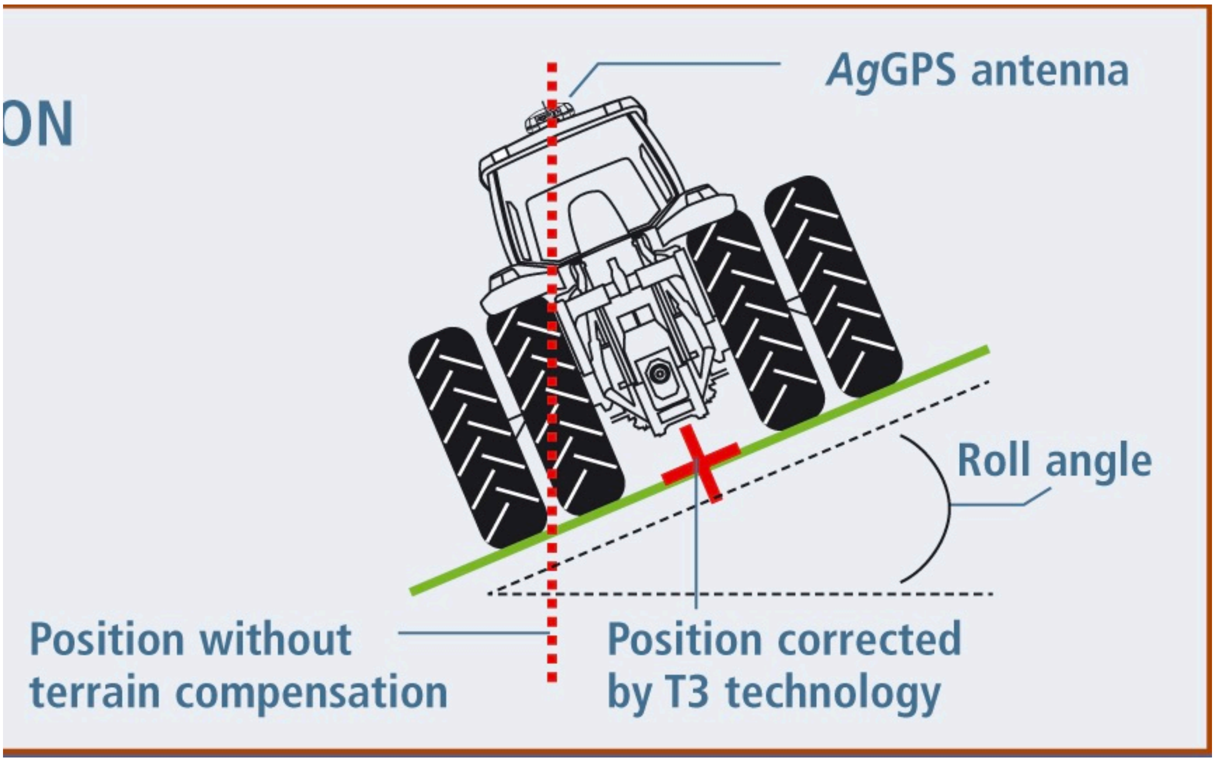


Figure 5. Terrain Compensation in the Roll Axis. (Source - Trimble Navigation)

Who provides the GNSS infrastructure
The US government developed the GPS system which first went fully operational in 1985. The Russian governments Glonass system then went fully operational in 2007. The European Galileo system is operating and expected to be fully operational in 2020. The Chinese BeiDou has been operating on a regional basis and is expected to be fully operational by 2020 as well. The GNSS signals are broadcast free of charge except for Galileo which charges a subscription for their high accuracy, 0.01m signal.

GNSS at High Latitudes
GNSS positioning has been available since 1993 and has founds its way in just about every navigation application in every part of the world. Scientists, explorers, and adventurers were quick to adopt the new technology and apply it everywhere they went. Their early experience was achieved using GPS receivers at a time when GPS was still subject to SA. In addition, with only one constellation of satellites available for positioning an increase in latitude did result in a reduction of visible satellites and a GPS fix was not always possible. That early experience turned into urban, or in this case, wilderness myths on the accuracy and usability of the GPS, especially in high

latitudes.   Nearly 24 years later, SA is turned off, and 4 GNSS constellations currently provide a combined 99 operational satellites and a further 52 satellites planned by 2020. Our tests and the Trimble GNSS Planning tool indicate that accurate navigation in the high latitudes is no longer constrained by satellite availability.

Future Developments

GNSS system development, GNSS receiver design, and GNSS infrastructure have developed rapidly over the last 40 years. New technology rapidly obsoletes existing technology rendering whole design strategies and infrastructure systems obsolete. The demand for accuracy is like speed in motor cars and memory storage in computers: users can't get enough. At huge cost, nations have developed their own GNSS and augmentation infrastructure in order to remain independent and free from limitations that might be imposed by the operators of the exisiting systems.

With a cell phone providing +/38mm (10mm in the future) with a 95% confidence level it is hard to imagine a dynamic application that requires higher accuracy. Improvements will come in improved performance in urban jungles and other areas where access to satellites is poor. Time to first fix will reduce. Positions will update faster. Reliability, and interoperability with other positioning technologies will increase. For most civilian, ground based dynamic applications, the GNSS currently provides sufficient positional accuracy.

Trimble GNSS Planning Software

In the early days of GPS and limited satellites it was necessary to plan in advance for any mapping and survey work to coincide with times of high satellite availability and low DOPs. The satellite schedule, or ephemeris could be downloaded from GPS.GOV and used to predict satellite status using software like Trimble's GPS planning software. Experience in the field did not always match the software's predictions reducing the confidence level in the software's usefulness. These services are now all available online, giving quick and accurate satellite status.

GNSS Mapping, Machine Guidance, and Machine Control for Land-based Navigation

GNSS Mapping is a process of recording the position of attributes on a GNSS map or in a Geographic Information System (GIS) data base. In their most basic form attributes include points, lines, and area features. Additional information is usually added to complete the data base. In the field a GIS (including a GNSS) can provide information on the location of the attributes, distance, heading, and estimated time to arrival based on the current GNSS position. Some GISs include a guidance interface that presents the information to an operator in a form that facilitates simple navigation.

GNSS Guidance systems provide guidance information to an operator that enables the operator to place the machine on a predefined location. In a dynamic environment the guidance system displays information that shows the operator where the machine is, where the desired location is, the distance from the feature, a time to the feature based on the current speed and heading, and a heading to the feature.

Accurate and convenient navigation information has made a significant contribution towards the advancement of modern society and is utilized in a number of applications to achieve advantageous results. Vehicles (e.g., planes, cars, tractors, boats, construction vehicles, etc.) have facilitated increased productivity and reduced costs in a variety of areas including transportation, construction, farming, defense, etc. The benefits provided by these vehicles are often dependent upon an operator's ability to accurately navigate a course along a designated path. However, vehicle operators typically do not have the pure natural sensory ability to precisely navigate a particular course unaided and they are usually dependent upon devices that provide navigation assistance. For example, it is often relatively difficult for an operator to keep a vehicle on a particular navigational line and heading. Due to the relatively complexities and attention required to operate numerous vehicles it is important that the navigation information be provide in convenient and easy to perceive formats.

Efficient navigation usually provides resource conservation and increased activity benefits. For example, accurately guiding a vehicle such as a ship or plane along a straight line path between a launching point and destination typically saves fuel and time. Accurately guiding a vehicle is also important in avoiding dangerous conditions (e.g. shallow waters, mountains, etc.) Vehicles are often used to perform tasks in which relatively precise navigational operation provides increased production results. For example, it is often advantageous for tractors and other vehicles utilized in farming operations to accurately follow uniform row designs during planting, dusting and harvesting crops. Following uniform rows during these activities usually facilitates increased production with the expenditure of reduced resources. For example, accurately navigating agriculture patterns helps assure seeds are located in the appropriate portion of a row, pesticide spraying actually hits the crops, and crops are not missed during harvesting. (Ahearn et al 2003)

GNSS Machine Control systems bypass the human operator and take direct control of the machine. Removing the human's natural variability improves accuracy and productivity is further increased. Benefits include higher accuracy, extended working hours, consistent operation, and the ability to interface with other positioning technology or groups of machines. The human benefits from reduced stress and reduced fatigue (Knepp).

Land-based navigation includes navigating a vehicle along a predetermined path such as a road, navigating to a waypoint where there are no roads, or following a pattern in an agricultural field.

Critical factors for successful machine control include:
1. 100% availability,
2. accurate and precise navigation within the confidence levels,
3. manual backup system,
4. technical support,
5. safe operation.

Land Based Machine Guidance and Machine Control Applications
GNSS machine guidance and control can be broken down into 2 dimensional applications and 3 dimensional applications and then classified by the accuracy level required for each application. At the high latitudes of Scott Base the limitations imposed by the GNSS augmentation services will direct which machine control systems can be used.

1. Autonomous - Low accuracy steering, +/- 2 to 5 metres,
2. RTX RangePoint - Low Accuracy steering, +/- 500mm,
3. RTX CentrePoint - Medium accuracy steering, +/- 100mm,
4. RTK - High accuracy steering and 3D land forming, +/- 10mm.

This project will focus on low accuracy steering for simple applications that are low priority.

Projects
This project began with a solution looking for a problem. My experience with machine guidance and machine control and the benefits it could provide made me think that with all the machinery operating at Scott Base, there must be an application that would benefit from GNSS machine control.
My experience with introducing new technology to organisations is that staff always hold preconceived ideas and expectations of what is possible and what is unusable for their special application. This is usually based on someone's prior experience and is often negative. I would come across the same expectations at Scott Base and was not surprised.

A useful application for GNSS is mapping and course following. The Scott Base staff had already explored mapping a road in a Hagglund, and then using the Garmin GNSS to retrace their path. Not surprising at the time they were disappointed with their test, and they consigned the idea to the "does not work here" basket. On following up on their experience I found the usual reasons why they had failed:

- the GPS unit was not accurate enough,
- the GPS antenna was not installed in the centre of the machine,
- The moving map display did not provide guidance to the operator on off-line error or heading required to get on-line.
- The operator was not trained in the use of a machine guidance display and soon lost confidence in the system.

My experience has shown that once an organisation loses confidence in a technology, it can takes 3 to 4 years for them to revisit the technology.

I explored several applications of the technology with them including:

- Search and rescue operations that would guide a vehicle to a known location and back again with limited input from the operator,
- Operations in condition 1 weather, where visibility is reduced to near zero, and it becomes impossible to visually navigate even on predefined paths,
- Laying out a transect to enable a research team to drive repeatability along the same path year after year,
- navigation to a fixed point or on a heading to a known location.

The aim of my project is to introduce Scott Base staff and Antarctica New Zealand to GNSS machine control and the benefits it might have in Antarctica. From a commercial perspective, sales of this equipment for use in the Antarctic is not my goal. It is a long way away, expensive to get to, and the sales volume does not justify the effort. However, I would like to support New Zealand's scientific programme so I propose letting Scott Base use my company's equipment on long term loan at no cost. The benefit to me is that I or my staff may get to travel to the Antarctic to complete installations and train Scott Base staff in its use.

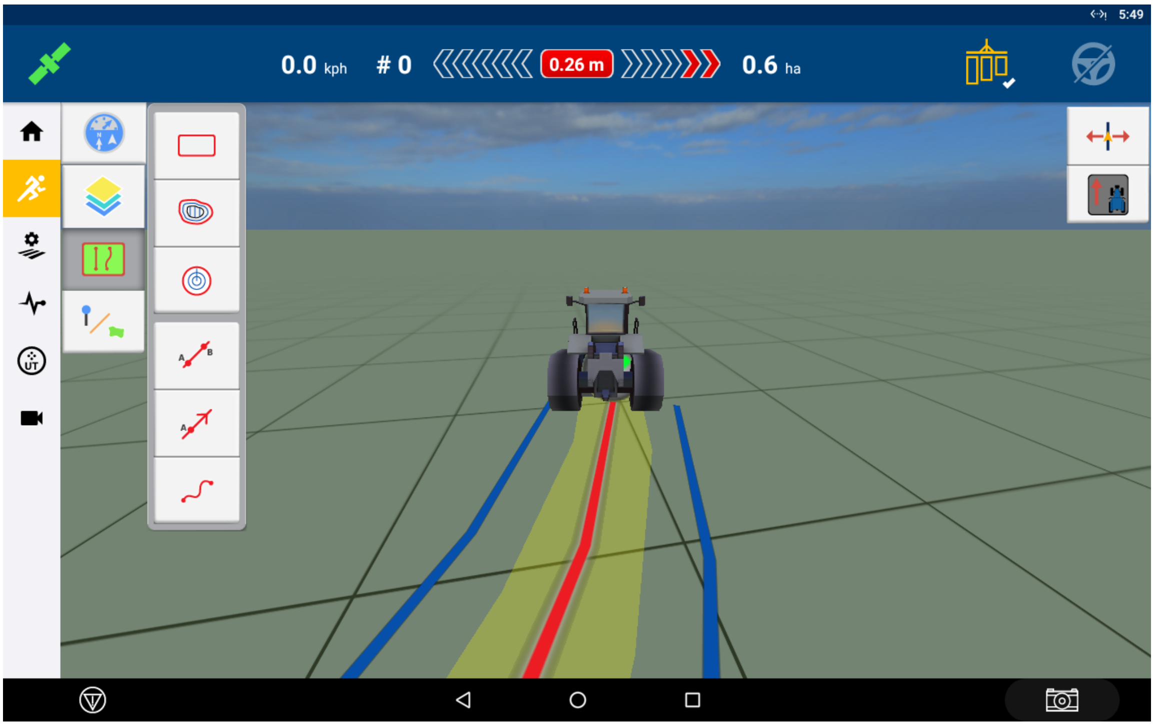


Figure 6. Trimble GFX Display - screen snap, recording AB line mode.

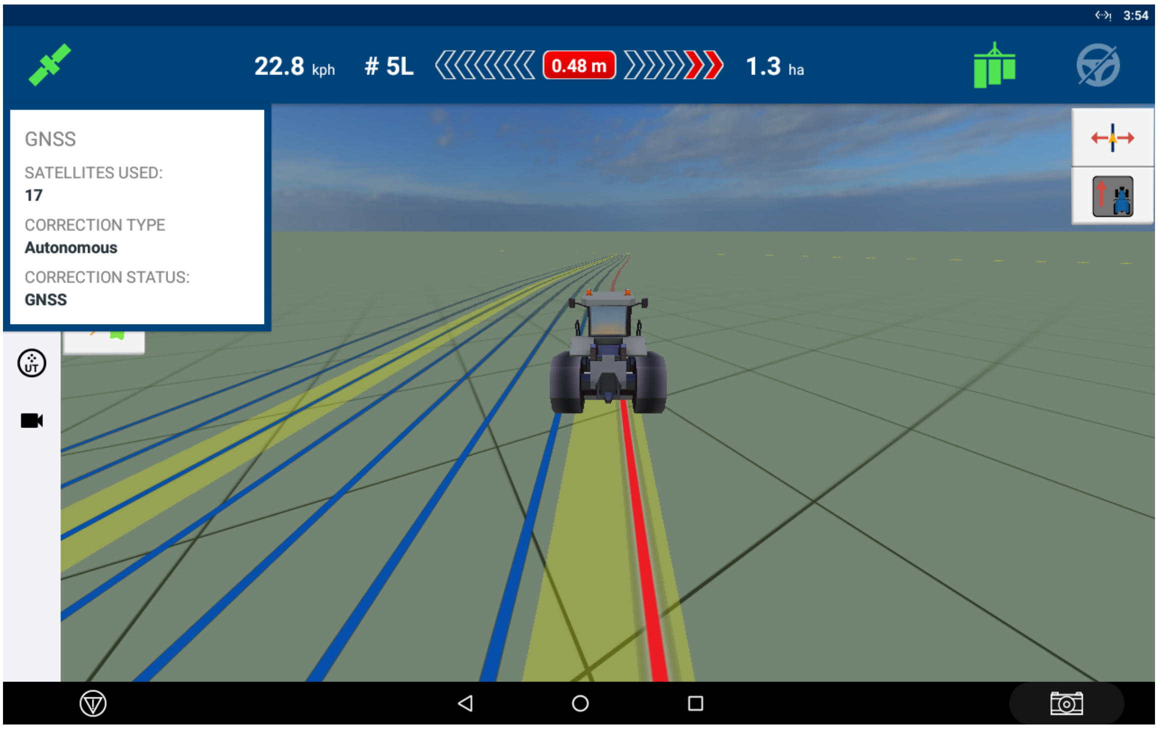


Figure 7. Trimble GFX Display - screen snap, in autopilot mode following the red guidance line. Note the low satellite numbers with only GPS and Glonass in use.

Ross Ice Shelf Programme
Participants include: University of Otago, Victoria University of Wellington, University of Canterbury, University of Waikato, University of Auckland, GNS Science, NIWA, UC Santa Cruz, Georgia Institute of Technology, Lamont-Doherty Earth Observatory.

The programme is aiming to understand the impact of climate change on the Ross Ice Shelf. A hole will be drilled through the ice shelf in order to study the ocean below, using a range of instruments and a remotely-operated submersible vehicle. A permanent instrument array will be installed allowing the team to see how the ocean under the ice changes with the seasons. Samples of the sea floor sediment will be taken to give insight as to when the last ice age ended. Seismometers will be installed in the ice to measure the internal properties of the ice shelf. Measurements of the atmosphere will continue to establish a link to ice shelf behaviour.

At the beginning of the season a convoy of equipment is driven 822km from Scott Base over the Ross Ice Shelf to the drilling site. The lead vehicle, A Piston Bully, is fitted with a ground-penetrating radar to detect crevasses before the vehicles fall in them. The trip takes over three weeks to get there and would be an ideal application for a self-steering system to reduce the stress and fatigue of the drivers. (Fig. X)

Figure 8. Crevasse detection - the hard way. (Source. Antarctica NZ)

Antarctica NZ field training instructor Tom Arnold tests out a crevasse-detecting radar that will be used by a research expedition to a remote site on Antarctica's Ross Ice Shelf. Photo / Supplied

Figure 9. Crevasse detection the latest way.(Source. Antarctica NZ)

Field Trip 1

During the field trip component of the 2017/18 PCAS course, I installed a Trimble GFX guidance system on to a Hagglund and on a Toyota Landcruiser with the aim of collecting GNSS performance data and comparing this with the predicted performance. The actual performance of the system would indicate which GNSS machine guidance systems would work in the Antarctic.

I spent time with the engineering and field staff at Scott Base to learn more about their experience with GNSS and to see if they had any applications that would suit GNSS machine control.

The testing provided results that indicate that the Trimble GFX system operating in autonomous mode provides a level of accuracy and reliability that is suitable for machine guidance applications where an accuracy of less than +/-500mm is required.

RTX CentrePoint and RangePoint corrections are not useable in the area around Scott Base due to the high latitude, and this reduces the number of applications possible for GNSS guidance and control systems.

RTK operation can be expected to work to its standard accuracy and performance in the Antarctic due to the high number of satellites available.

Scott Base Engineering staff are actively looking for a guidance system that can be used on their Piston Bully for the Ross Ice Shelf Program.

A site visit by John Evans to test the Trimble GFX machine control system operating in autonomous mode on an agricultural vehicle will demonstrate that the Trimble GFX machine control system can be configured to meet the requirements of the Piston Bully for the Ross Ice Shelf Program.

This field trip report is included in Appendix 1

Field Trip 2.
Following the successful field trip in Antarctica, I invited John Evans from the engineering team to visit a farm in New Zealand to learn more about GNSS machine control and how this could be implemented in a Piston Bully at Scott Base.

The field trip was a great opportunity to introduce John Evans to a GNSS self-steering system working in a field and show him its simple configuration and operation. John's knowledge of the Ross Ice Shelf Program and the Piston Bully enabled him to ask questions about the operation of the self-steering system that related directly to his requirements.

We are able to now configure a self-steering system that will meet his requirements using a trimble GFX machine control system..

This field trip report is included in Appendix 2

Conclusions
Advances in GNSS technology over the last 25 years, and the proposed developments in the future will remove previous limitations and increase the availability of the GNSS world-wide.

The introduction of multiple GNSS constellations has had a significant affect on the usability of GNSS in high latitudes.

The Scott Base engineering team has the interest and the will to proceed with testing a GNSS machine control system. Machine control technology could provide significant assistance to programmes at Scott Base.

The Ross Ice Shelf Program provides an opportunity to install a machine control system on a Piston Bully to assist with the 822km transect to their drilling site.

Recommendations
A Trimble GFX machine control system should be prepared for installation on the Piston Bully at Scott Base in the spring of 2018 for use on the Ross Ice Shelf Program.

Following installation, the Trimble GFX should be used to introduce Scott Base staff to GNSS machine control, and train them in its use.

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Appendix 1
Field trip 1. Scott Base, Antarctica
John Ahearn
3rd February - 14th February 2018

Introduction

While at Scott Base to complete the field study component of my PCAS, I made contact with the Scott Base engineering group to discuss testing a Trimble GFX (Trimble) guidance system on one of their vehicles. The Trimble GFX uses satellite data from 4 GNSS constellations and has only been in production since December 2017. This will be the first performance testing of the system at high latitudes. A significant improvement in performance has already been observed at lower latitudes. The Scott Base testing will evaluate the accuracy and usability of the system for machine control in machines at high latitudes where GNSS performance has been previously unreliable (Ruotsalaienen) (Jensen) . The system was mounted on two different vehicles and performance recorded for later analysis.

The actual performance will also be compared to theoretical performance as predicted by Trimble GNSS planning (Trimble Planning) software - that predicts satellite availability and accuracy.

The aim of the testing was to determine if the performance of the Trimble GFX guidance system was capable of providing accurate and reliable guidance suitable for machine control operations at Scott Base.

Method
The Trimble GFX guidance and machine control system has three main components: the antenna and terrain compensation module which is mounted on the roof, the display screen which is a touchscreen display running embedded Trimble software on an andriod operating system, and a steering actuator. The steering actuator is not required for data collection so this was not installed which kept the process simple with the minimum disruption to Scott Base operations.

The system was installed on a Hagglund that transported our PCAS group to the Windless Bight Field camp, and later to Castle Rock, and around Scott Base. Later on it was installed on a Toyota Landcruiser, and data was collected on the roads around Scott Base.

Installation of the system needed to be quick and simple with the minimum disruption to the schedule of operations. The Trimble GFX antenna has a magnetic bracket that was used to mount the unit on the Hagglund steel roof frame (Fig. A1. 1). The magnetic bracket mounted directly on Toyota's steel roof. The display was mounted on the dashboard in each vehicle using a vacuum mount. The system was connected to 12 volt power supply via a cigarette lighter plug.

Fig A1 1. Trimble GFX Antenna mounted on the Hagglund.

The system was operated during normal driving activities of the vehicles on routes that might be expected to be used around Scott Base where self-steering might be useful. Normal operation of a guidance system requires a route to be recorded for later play back. The route can then be driven again using the system to provide guidance along the pre-recorded path. If a steering actuator is fitted, this will control the vehicle's steering and drive the vehicle along the recorded line. Point, line, and area attributes can be recorded at any time and these will be displayed on the Trimble moving map display.

The Trimble GFX can be configured to use a GNSS correction signal from an SBAS or a GBAS to improve the accuracy of the position. GBAS was not tested because this would require a GNSS reference station to be setup at Scott Base which was not available. The SBAS signal will be tested for reception and accuracy.

Trimble planning software can be used to predict GNSS satellite coverage anywhere on earth. The predictions will be compared with the actual performance of the Trimble GFX.

Performance data is gathered directly from the display using screen snaps (Fig A1, 2 & 3).

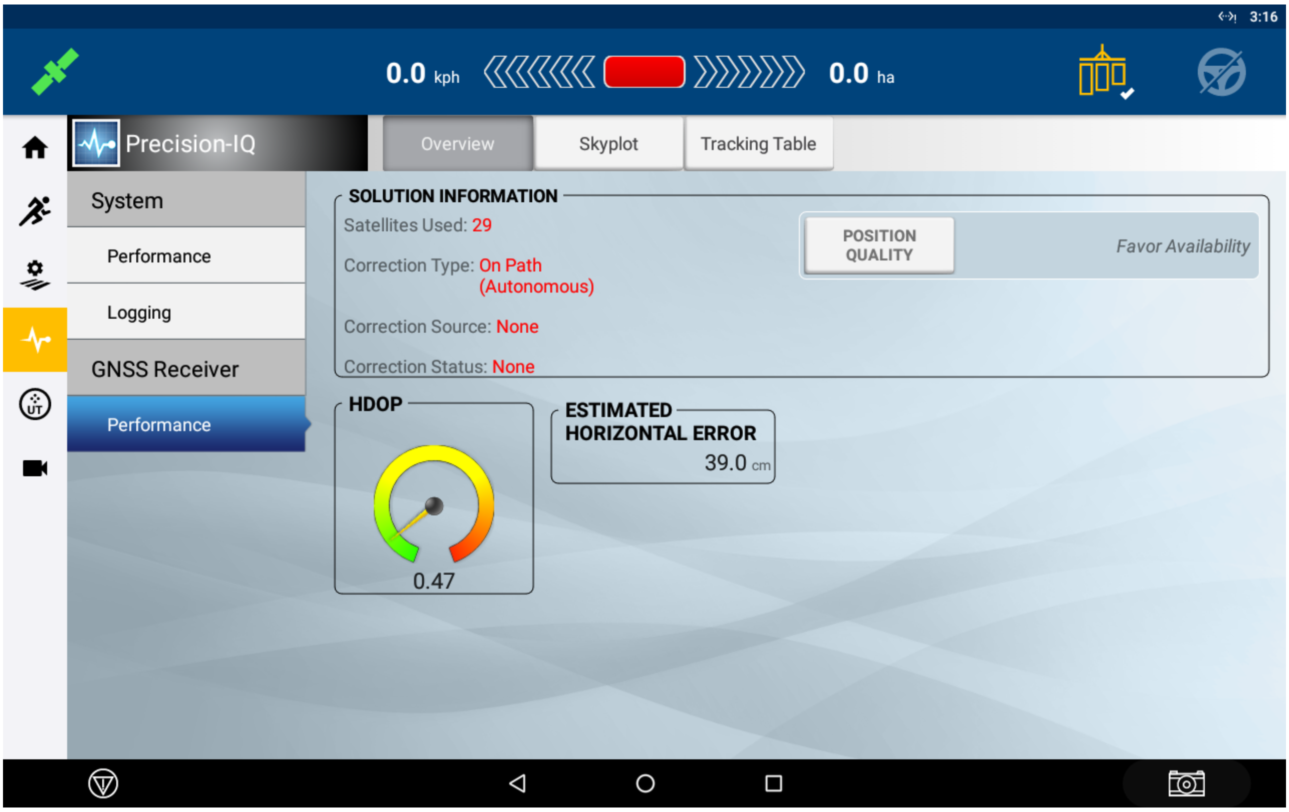

Figure A1 2. Screen snap from the Trimble GFX Display showing satellites used, HDOP, and Estimated Horizontal Error.

Figure A1 3. Screen snap from the Trimble GFX Display showing satellite skyplot.

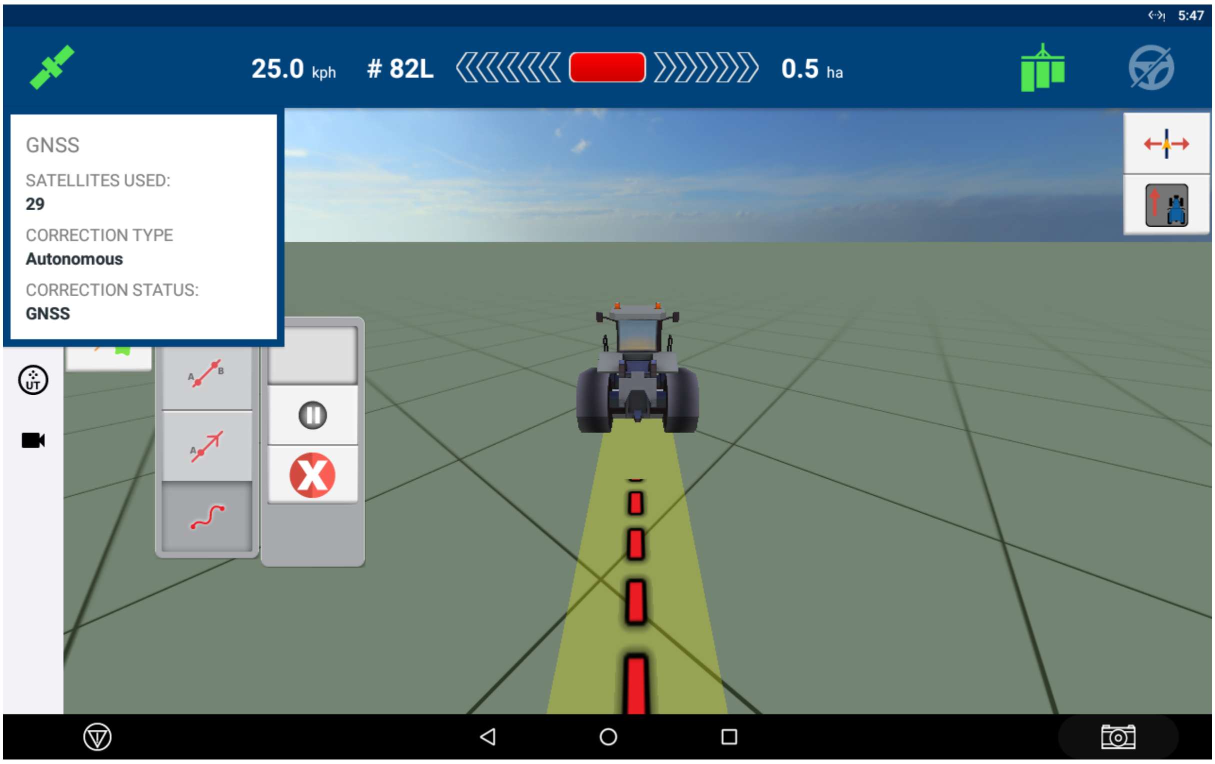

Figure A1 4. Screen snap from the Trimble GFX Display showing A+ line recording for later playback.

Results

The testing provided the first position data from Trimble's GFX system working at high latitudes and using the 4 GNSS constellations. The testing was completed over 10 days with approximately 15 hours of performance data captured.

1. Satellites used

   The system can track satellites in the GPS, Glonass, BeiDou, and Galileo GNSS constellations. When using all 4 constellations during the test period the number of satellites ranged between 24 and 32. Position accuracy is improved with access to more satellites.

   The Trimble Planning software predicted a range of 24 to 33 used satellites over a 24 hour period (Fig. A1 5).

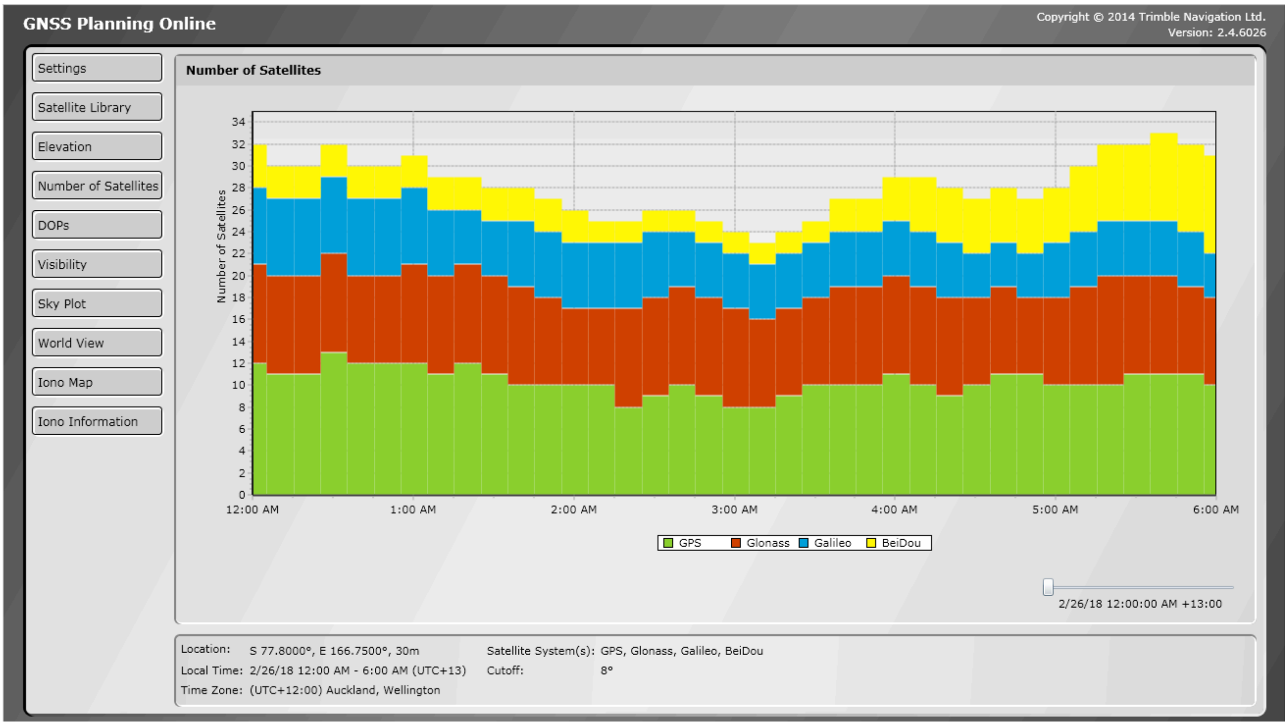

Figure A1 5. Trimble GNSS Planning software showing satellite availability.

2. Correction Type (Augmentation Systems)

   The Trimble GFX can be configured to operate with an SBAS or GBAS correction signal to improve accuracy. It can also operate in autonomous mode when a correctional signal is not available.

   A. Autonomous mode testing was successfully completed, and the results are shown below.

   B. SBAS - RTX Centrepoint and RTX Rangepoint corrections are broadcast from a geostationary satellite. Reception was tested around Scott Base and at the Windless Bight. A signal was not received at any of the locations tested. A final attempt to access the signal was made by driving to the highest north facing location that the Toyota could obtain with no success. RTX Rangepoint when available is accurate to +/- 500mm. RTX Centrepoint is accurate to +/-40mm.

C. GBAS - RTK correction signals provide an accuracy of +/-25mm. RTK operation is limited when the number of useable satellites available is less than 5. With the tests confirming reception of more than 24 satellites all the time, testing RTK operation was not required.

3. HDOP

The HDOP provides an indication of the accuracy of the solution. It is a non dimensional number - a number less than 3 will provide reliable positions that lack variability or random jumps in position due to changes in satellite geometry. Fig. A1 2 shows a HDOP of 0.47. A HDOP greater than 1 was not observed during any testing. A HDOP less than 3 is considered acceptable for machine control.

The Trimble Planning software predicted a HDOP (GPS, Glonass, BeiDou, Galileo) of less than 0.6 over a 24 hour period.(Fig.A1 6).

The Trimble Planning software predicted much greater variation in the DOPs when just the GPS and Glonass satellites are used at the same location over the same 24 hour period.(Fig. A1 7).

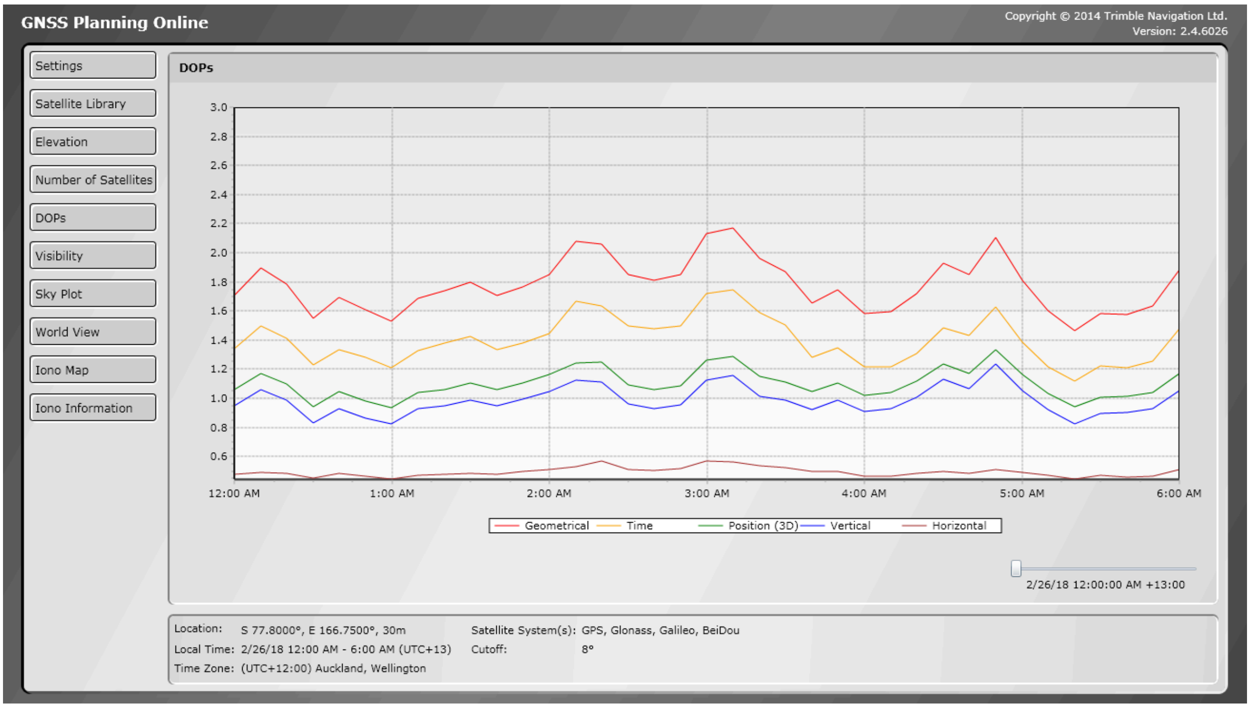

Figure A1 6. Trimble GNSS Planning software showing GNSS DOPs for GPS, Glonass, BeiDou, and Galileo satellites.

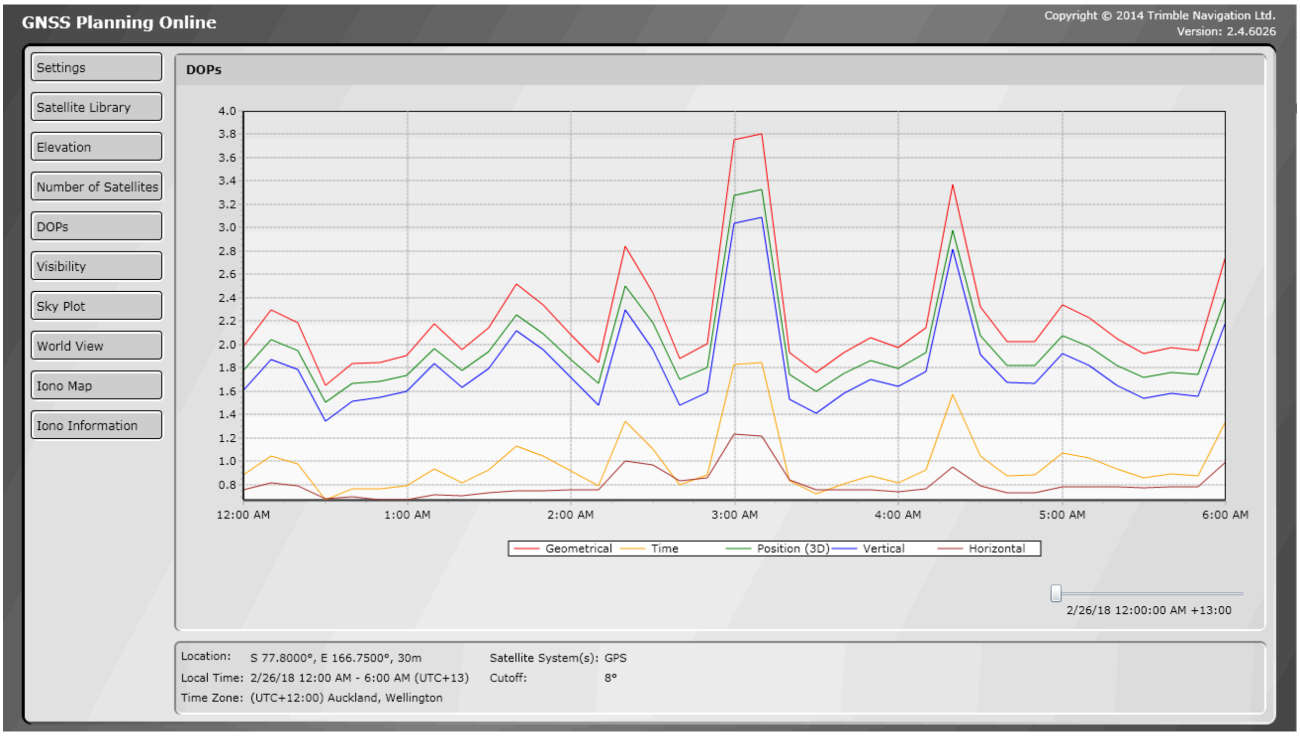

Figure A1 7. Trimble GNSS Planning software showing DOPs for GPS and Glonass satellites.

4. Estimated Horizontal Error

   The Trimble GFX provides a continuous display of the estimated horizontal error of the position. For guidance and machine control applications this is the most important variable when comparing configurations. The horizontal error was not observed to exceed +/- 500mm during any testing.

5. Static Accuracy

   Data was collected from a 24 hour static test. This was to be used to conduct an analysis that would show a scatter diagram of positions. Typical analysis shows the range of positions that can be expected with 1, 2, and 3 standard deviations from the mean. Unfortunately the data file became corrupted during the download from the Trimble GFX. The embedded software crashed 4 times during the testing at Scott Base. While frustrating this is not unusual with a new product that has only recently been released.

6. Trimble Planning Software

   There was strong correlation between actual observed satellite numbers, and HDOP figures with the Trimble planning software predictions. This creates a high confidence level that future performance can be predicted using the Trimble Planning software.

7. Staff feedback

   Installation and testing of the Trimble GFX created an opportunity to discuss with Scott Base staff their experiences and expectations of GNSS mapping and guidance systems.

   The engineering staff took a positive interest in the testing. Scott Base engineer John Evans had been looking at GNSS guidance and control systems to retrofit to the Piston Bully 100 (Fig. A1 8). This vehicle is used to mark out the route for the convoy to follow that takes the equipment out to the Ross Ice Shelf Program's drilling site. The Piston Bully is fitted with a ground penetrating radar to detect crevasses as it drives along. Steering accuracy is not critical with a error of +/- 1 metre being acceptable over the 822km route that takes more then 3 weeks to complete.

   The field staff had attempted to use a Garmin GNSS receiver to map roads around Scott Base for later use in limited visibility. This was not successful and they had a negative view of the usefulness of such a system.

Discussion

Prior to the Trimble GFX system coming to the market, the GNSS receivers used in machine control applications used only the GPS and Glonass GNSS satellites constellations. It was necessary to use a correction signal to achieve low accuracy positioning. The addition of the Galileo and BeiDou constellations has significantly increased the number of satellites for operation, and decreased the HDOP figures. The testing has shown that when operating in autonomous mode with 4 GNSS constellations, the accuracy achieved is similar to operation with RTX RangePoint corrections.

The unavailability of the RTX CentrePoint correction service was not expected. This service provides a cost effective solution that is cheap to operate and is ideal for most mid level accuracy machine control applications. The unavailability reduces the opportunity for GNSS machine control applications in the Antarctic.

The testing created an opportunity to introduce Scott Base engineering staff to the Trimble GFX system and show its operation on one of their machines at their location. From a sales prospective this is usually an excellent way to get customer-buy-in and interest in the product. John Evans will return to New Zealand at the end of the summer program and take the opportunity to visit one of our customer sites to see a machine control system in operation. This will provide an opportunity to evaluate the features against the requirements for the Piston Bully project.

The experience of the field staff with their Garmin GNSS receiver is not uncommon. There are some fundamental factors to consider and to get right when setting up a machine for guidance.   The accuracy of the GNSS receiver is important when mapping a line and then retracing it. GNSS accuracy on a GPS/Glonass mapping receiver moves randomly at about 1 metre per hour with a range of about +/- 5 metres. So a line feature recorded and then played back hours later may show an error of up to 10 metres. It might also show an error less than 1 metre and appear perfect. The mounting of the GNSS antenna is important. The Garmin used for the test had its antenna mounted on one side of the roof (Fig. A1. 8) which is fine when travelling the same direction as the recorder. However, on a reciprocal heading the antenna will be on the other side of the line introducing a roof-width error to the position. To provide effective guidance the moving map display of the GNSS should be mounted directly in front of the driver and show him an offline distance, a heading to get back on line, and calculate this information for 1 second in advance to allow the driver to respond in time. There are some important differences between a GNSS mapping unit and a GNSS guidance unit. For the field team it will take some positive experiences with GNSS guidance and control systems to eliminate the negative attitude that their previous experiences generated.

Figure A1. 8. Garmin Antenna on the Hagglund roof.

Conclusions

The testing provided results that indicate that the Trimble GFX system operating in autonomous mode provides a level of accuracy and reliability that is suitable for machine guidance applications where an accuracy of less than +/-500mm is required.

RTX CentrePoint and RangePoint corrections are not useable in the area around Scott Base due to the high latitude, and this reduces the possible applications for GNSS guidance and control systems.

RTK operation can be expected to work to its standard accuracy and performance in the Antarctic due to the high number of satellites available.

Scott Base Engineering staff are actively looking for a guidance system that can be used on their Piston Bully (Fig. A1. 8) for the Ross Ice Shelf Program.

A site visit by John Evans to test the Trimble GFX machine control system operating in autonomous mode on an agricultural vehicle will demonstrate that the Trimble GFX machine control system can be configured to meet the requirements of the Piston Bully for the Ross Ice Shelf Program.

Fig. A1 9. Piston Bully 100 - PB01.

Appendix 2.
Field Trip 2.
Machine Control Demonstration - Agriculture

John Ahearn, GPS Control Systems
Russell Van de Laak, GPS Control Systems
John Evans, Antarctica New Zealand (NZ)
Andrew Smith, Turley Farms, Temuka

1st March 2018

Introduction
The primary application for machine control in agriculture is to steer a machine on a predefined path. In its simplest form this is steering a tractor along a straight line, the AB line. The operator creates an AB line by driving the path, or inputting the co-ordinates of the path he wants the tractor to follow. The tractor will then steer along multiple, parallel lines of that AB line as it performs operations in the field including cultivation, planting, spraying, and finally harvesting (Ahearn et al). These simple and accurate self-steering systems have applications outside agriculture. Driving a perfectly straight line requires skill and concentration that causes stress and fatigue and is easily replicated using a GNSS machine control system. Freeing the operator from the constraints of continuous steering and constant concentration on the heading allows him to monitor other activities in the cab (Knepp). A visit to a farm to view agricultural machines using the technology will help identify strengths and weakness in the application of the technology to the Antarctic for driving long-distance transects.

Setting realistic expectations for new technology is a key to the successful implementation of that technology in an organisation.

Methods
The aim of the field trip was to introduce John Evans of Antartica NZ to GNSS machine control in an environment that he was familiar with. John works in the engineering department at Scott Base, Antarctica. His role includes engineering support for the Ross Ice Shelf Program which uses a Piston Bully with a crevasse-detecting radar (Fig. A2.1) to lead the convoy out to the drilling site in early summer. At the end of the 2017/18 summer season, John was back home on the family farm near Temuka in South Canterbury. Nearby I have a number of customers using GNSS machine control systems for farming operations. Murray Turley is a keen supporter of the Antarctic Heritage Trust so we went to his farm to view some of the 13 self-steering systems in action on his tractors, sprayers, and combines. This created an opportunity to visit and meet with the operators, ride in the machines, and see first-hand how the systems operate in the agricultural world. John would be able to see examples of hydraulic and electric steering actuators in wheeled and tracked machines. There would be an opportunity to set-up a guidance pattern and observe the machine's performance when steering along the pattern. Talking with operators would introduce John to the day-to-day operations of self-steering, the benefits and limitations. The knowledge and experience gained during the field trip would then help John to set realistic expectations on what could be achieved in the Antarctic with self-steering and mapping systems.

Antarctica NZ field training instructor Tom Arnold tests out a crevasse-detecting radar that will be used by a research expedition to a remote site on Antarctica's Ross Ice Shelf. Photo / Supplied

Figure A2. 1. Piston Bully with crevasse-detecting radar. (Source. Antarctica NZ)

Results

Russell of GPS Control Systems took John for a ride in a Case tractor that is fitted with Trimble Autopilot self-steering. The aim was to show John how the operator sets up a guidance pattern. There are multiple patterns, but the main one we wanted to show John was the A+ method. The operator sets a heading, in this case we used 180 degrees (true south), and set an origin - which in this case was the tractor's current position. The Autopilot system then generates a guidance line based on its GNSS position. The operator engages the autopilot, and puts the tractor in to drive. The tractor will steer itself along that line with an accuracy to match the accuracy of the GNSS system being used. For our field trial this was +/- 25mm; however, in the Antarctic this would be +/-500mm. To disengage, the operator simply turns the steering wheel and the autopilot disengages in a similar way to cruise control disengaging when the driver touches the foot brake.

The operator can add attributes to the Trimble moving map display as the tractor moves along the line. Point, line, and area attributes can be recorded, and these will show up on the moving map display depending on the their proximity and the scale of the map.

Discussion

Every application for self-steering has its own requirements, limitations, and opportunities that are distinct to that application. There are also many factors that are common to every application. It is not until an operator has an Autopilot on his machine in his environment that he truly learns what the system can do for him. I call this the lightbulb moment when he understands how it will impact his operation. Putting John in a machine in a familiar environment while not quite the same as Antarctica, would give him an opportunity to generate questions about the operation on his machines in his Antarctic environment. We discussed aspects of the operation including:

1. Turning angle

   The Piston Bully tows up to 4 sledges behind it on the transect to the drilling site. Once these sledges are all connected to the Piston Bully, the train behind creates a vehicle that will not respond well if the steering angle of the lead machine is to great. The self-steering system will need to have a maximum angle of turn to prevent undue stress on the towing linkages. Sharp turns will also make a difficult path for the following towed sledges to follow.

2. Aggressiveness

   The control system uses a proportional, closed-loop feedback control that can be adjusted for the aggressiveness of the steering inputs. The proportional gain of the control algorithm is adjusted to suit the application. A high proportional gain (P gain) setting will steer aggressively and get on-line quickly with a series of aggressive S turns that reduce the on-line error to zero. This is useful for farmers requiring the minimum amount of time to get on-line. The Piston Bully operation is not concerned with time to get on-line, so the P gain will be set low to reduce the aggressiveness of the steering inputs.

3. Speed

   The Trimble Autopilot system is designed to operate within a speed range of 0 to 50km/hr where self-steering remains stable and controllable. The Piston Bully will operate at the lower end of the speed range.

4. Driver attention and fatigue

   The transect across the Ross Ice shelf to the drilling site is 822 km long and takes more than 3 weeks for the Piston Bully to complete. Visibility ranges from zero to over 50km. Whiteouts are common, and these cause the horizon to disappear - the continual monotonous steering into white on white causes fatigue and stress for the operator. Staying awake and alert to the constant danger of crevasses is further stress on the driver. Our experience in the agricultural sector has shown that reducing driver stress and fatigue is one of the main reasons farmers install self-steering systems on their tractors. Initially seen as a luxury, operators will report that they can do a 12 hour shift and come home not feeling as tired and exhausted compared to not having the system. Andrew from Turley farms was able to talk directly about his experiences with John.

   The Autopilot system has a driver-awake alert that can be set to activate at 3, 5, 10, or 15 minute intervals. An alarm sounds and requires the operator to acknowledge and re-set the alarm. Failure to acknowledge results in a 360 degree turn after 90 seconds. The Piston Bully train will require a different solution as it would be undesirable to put the train in to a 360 degree turn. Alternatively the system could be set to disengaged the transmission or cut power to the fuel pump to stop the engine.
5. System accuracy

   The system we demonstrated to John was running with an accuracy of +/- 25mm on the AB line. This level of accuracy is not required in the Antarctic; however, accuracy is important because if the error in the Piston Bully's position varies too much, it will result in a continual attempt to correct the position. The Autopilot system evens out the position and creates a smooth line to follow that is not affected by position drift. An accuracy of +/- 500mm will be accurate enough.
6. Combining radar and course monitoring

   The Piston Bully has a crew of two, the driver and the radar operator. Both crew members suffer from fatigue and stress as described above. It may be possible for the driver to monitor the radar screen for crevasses and also monitor the steering performance of the Autopilot system. This would allow the second crew member to rest and be available for driving duties later on which would extend the working day.
7. Hardware from other market segments

   GNSS machine guidance and control systems are used in agriculture, construction, mining, and marine markets. The Piston Bully application requires self-steering on a constant heading or to a waypoint without any additional complications. The simplicity of agricultural guidance and control systems makes them well suited to the Antarctic because they are simple and have been designed for harsh environments. Specialist training, skills, and knowledge are not required to configure and operate them. Farm workers quickly grasp the basic principles of operation following an on-screen menu system that leads them through set-up and operation. Russell was able to demonstrate to John just how simple this was.
8. Steering Interface

   An important consideration when installing a self-steering system on a machine is the method of actually controlling the steering. In agricultural machines this can be done with a proportional hydraulic valve connected in parallel (Fig. A2. 5) or series (Fig. A. 6) with the tractor's own hydraulic steering system. This solution is the most accurate and precise. Alternatively, an electric motor can be coupled directly to the steering wheel to provide steering input. These are less accurate but simple, reliable, and easy to retrofit to existing machines. Manufacturers are now delivering machines with fly-by-wire steering control which allows the self-steering system to direct-connect straight the tractor's computer steering control system.

The steering system in a Piston Bully is electric sensing with hydraulic actuation. We could interface to this system using a proportional valve in parallel to control the steering. This method of installation can require a lot of fine-tuning and adjustment before successfully steering the machine. The resources and time required make this solution difficult given the remoteness of the installation. A direct-connect to the fly-by-wire system would be ideal; however, this will require the Piston Bully manufacturers input, and this has not been forthcoming - so far. A simpler solution is an electric motor coupled direct to the steering wheel. There are two systems that would be suitable: Trimble EZ-Pilot (Fig. A2. 2), or Trimble EZ-Steer (Fig. A2. 3). The EZ-Steer actuator is lighter and simpler to install which would suit the Piton Bully's simple and less robust steering column. We could supply John with an EZ-Steer motor, so he could work on a mounting solution over the winter.

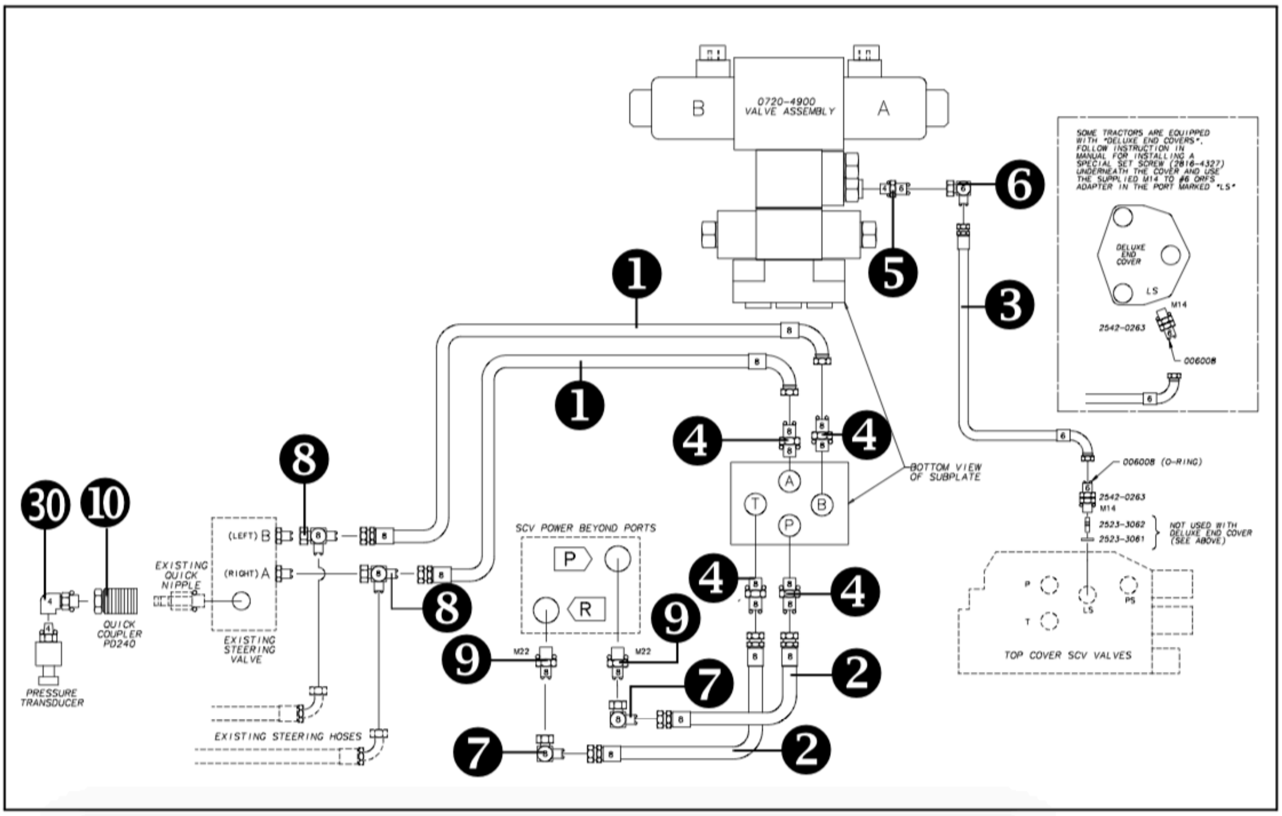

Figure A2. 2. Hydraulic Steering interface - Parallel connection for wheeled vehicles. (Source. Trimble Navigation)

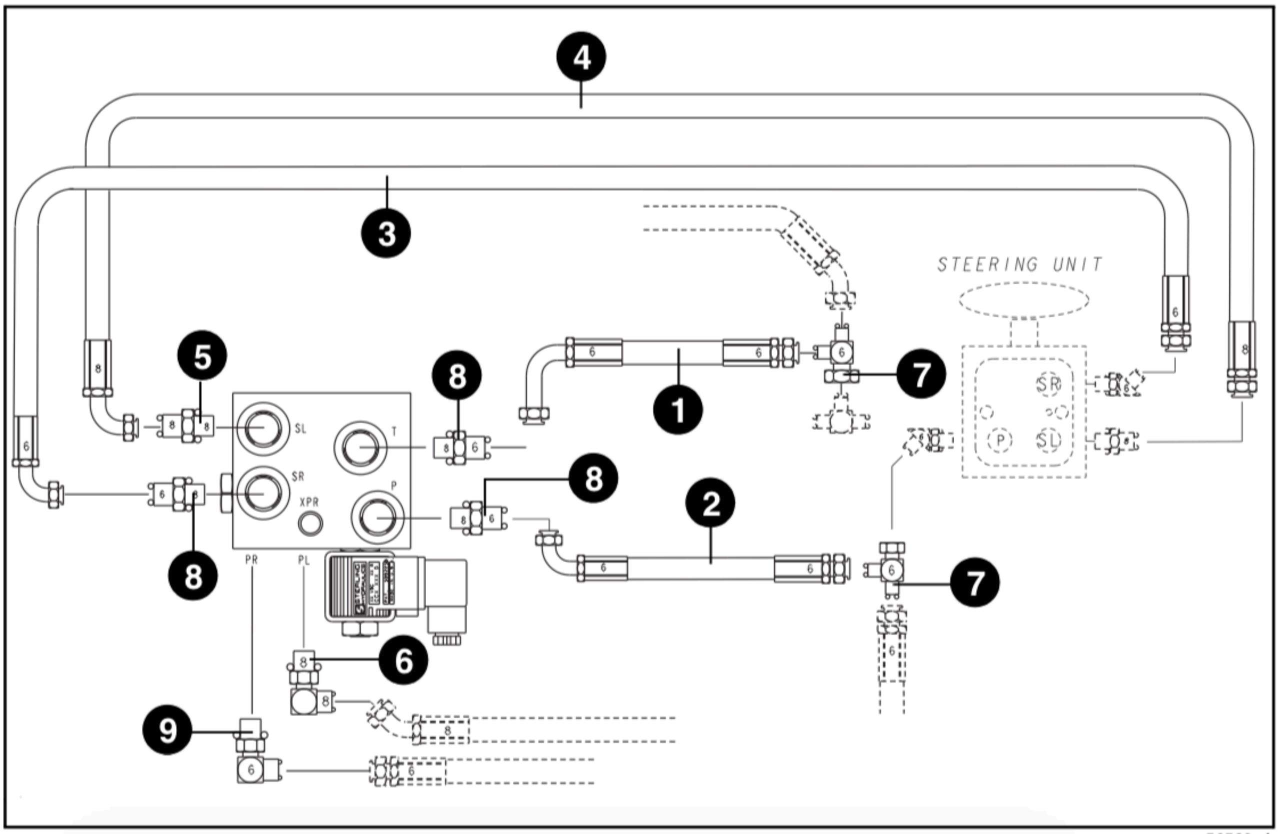

Figure A2. 3. Hydraulic Steering interface - Series connection for tracked vehicles. (Source. Trimble Navigation)

Figure A2. 4 shows the control column on the Piston Bully. The column rotates approximately 45 degrees either side of straight-ahead position. This is similar to the rotational movement on a John Deere rubber tracked tractor and a Cat Challenger rubber tracked tractor. The EZ-Steer system will successfully operate with this amount of steering column movement.

Figure A2. 4. Piston Bully Steering column - max deflection - 45 to +45 degrees.

Figure A2. 5. John Evans investigates Trimble EZ-Pilot in a McDon Swather.

Figure A2. 6. Trimble EZ-Steer mounted on a Case Tractor. (Source. Trimble Navigation)

9. The economic benefits

The economic benefits of self-steering for a farmer are easy to identify and model using an accountant's spreadsheet. Savings come from reduced inputs due to zero overlap between passes. Yields are increased due to accurate planting. Yields are increased due to accurate harvesting. Accurate driving allows bigger machines, and jobs get done on time. However, we find one of the most compelling arguments for installing self-steering is the reduction in stress and fatigue on the operator. An alert operator does not damage the machine or implement. They are quick to spot problems with the performance of a planter or harvester. They work a longer shift and are happy to do overtime. And their wives will tell you they come home happier and play with their kids.

The economic benefits of self-steering to Piston Bully would be insignificant when compared to the cost of the entire Ross Ice Shelf Program. The Antarctic summer presents a short time-frame for completing work. Any delays due to equipment failure, weather, staff, and accidents could delay an entire program for the entire season. Getting the Ross Ice Shelf Program equipment out to the drilling site without delay or accident is mission critical to a successful season. There are many factors that could impact the time to complete the transect. A GNSS self-steering system would reduce some of these factors:

- reduced fatigue and stress keeps the operator alert for crevasses and machine problems,
- single crew spreads the work load and allows time for rest,
- accurate driving keeps the train on route with minimum course correction,
- progress is maintained during low visibility,
- Health and safety are maintained.

10. How to introduce this technology to Antarctica

I have been involved in the introduction of this technology in the mining, construction, and agricultural industries. I worked in the engineering teams designing the first GNSS systems for helicopters and ships, and I later moved to sales and business management in the machine control industry. My experience has been that introducing new technology creates resistance to change from some staff and complete embracing from others. Successful introduction requires an agent of change within the organisation to champion the product and convince others of its usefulness and benefits. John Evans is the man for this role within Antarctica New Zealand. He has already investigated self-steering technology and spoken with the manufacturers of the Piston Bully. John's role in the successful introduction of the technology is essential to a successful adoption of the technology. There are already preconceived ideas about the usefulness of GNSS guidance in Antarctica, and they need to be addressed and the benefits experienced. When an operator has successfully used a self-steering system they become a believer in the technology. The tractor with self-steering is the first to be used, the one with the most hours, and the one everyone wants to drive. The success of this technology in the agricultural industry is best measured in the number of systems installed - Turley Farms will install their 14th unit in early 2018.

Some of these systems are only used during the 6 weeks of harvest, but the benefits are real. Otherwise farmers would not continue to invest in them.

11. Heath and Safety Benefits

Health and safety are taken very seriously in the Antarctic. Access to medical facilities is limited, and simple accidents are not simply cured due to the remoteness. Health and safety can impact work programs that only have limited windows of opportunity by creating delays that are also compounded by the remoteness of the area. A self-steering system will not eliminate accidents, but it can reduce the stress and fatigue that contribute to accidents.

Conclusion

The field trip was a great opportunity to introduce John Evans to a GNSS self-steering system working in a field and show him its simple configuration and operation. John's knowledge of the Ross Ice Shelf Program and the Piston Bully enabled him to ask questions about the operation of the self-steering system that related directly to his requirements (Fig. A2. 7)
We are able to now configure a self-steering system that will meet his requirements.

Figure A2. 7. John Evans with Andrew Smith, and Russell Van de Laak discuss the requirements for self-steering in the Antarctic.